Satellite Delivery of Wideband Services by ACTS

Douglas Hoder and Michael Zernic

NASA Lewis Research Center
Cleveland, Ohio USA

(dhoder@lerc.nasa.gov, mzernic@lerc.nasa.gov)

Abstract: In order to for a satellite system to deliver wideband services compatible with terrestrial fiber networks, several major technological obstacles needed to be overcome. The solutions used in the ACTS Gigabit Satellite Network provided varying levels of success. Three major concerns prevail.

The first set of problems concerns channel bandwidth and signal quality. Most terrestrial networks are capable of providing bandwidth in excess of 622 Mb/s (SONET OC-12) on a single fiber, and at error rates of less than 10^{-12}*. Although the ACTS satellite is capable of providing bandwidth for SONET service up to the OC-12 level, the construction of a ground station network required to utilize the ACTS bandwidth and get adequate error performance presented a major challenge.*

Another issue associated with SONET service over satellite is the physical layer compatibility with terrestrial SONET equipment and networks. These were dealt with throughout the design and integration of the GSN. The satellite TDMA system and terrestrial interfaces were designed specifically to accommodate SONET service. The integration of the network was done in a manner of increasing network complexity, beginning with simple point-to-point connections, and finishing with interconnection of existing terrestrial fiber SONET and ATM testbeds.

The final concerns arise from the incompatibility of the satellite path latency with communications protocols existing in the machines and applications connected to the network.

1) Introduction--Fiber vs Satellite

A space-based communications network can provide three primary functions--operating alone, as a bridge between isolated terrestrial networks, or as an extension to remotely-located terminal equipment.

Operating independently, a space-based network can interconnect remote or even mobile terminals. The obvious applications are for temporary, portable equipment, vehicular systems, aircraft and marine. Such systems usually incorporate proprietary equipment and protocols. These are in general, not compatible with terrestrial data networks.

As a bridge, a satellite can interconnect two or more terrestrial networks located in geographically remote locations. In this application, it is a requirement that the space-based service either conform to the protocols of the interconnected networks, or be capable of somehow terminating these protocols, in order that the data may be passed between and routed through the two networks.

As an extension, a space-based system can serve to connect remote or mobile nodes in a network. This is basically the same configuration as the bridge. However, the protocol problem may be somewhat easier to solve, as the ground station usually serves as an isolated node, with no routing beyond its local network. Thus, the protocols can be terminated at the ground station.

Further applications of satellite-based systems include the establishment of temporary service and alleviation of congestion in terrestrial systems.

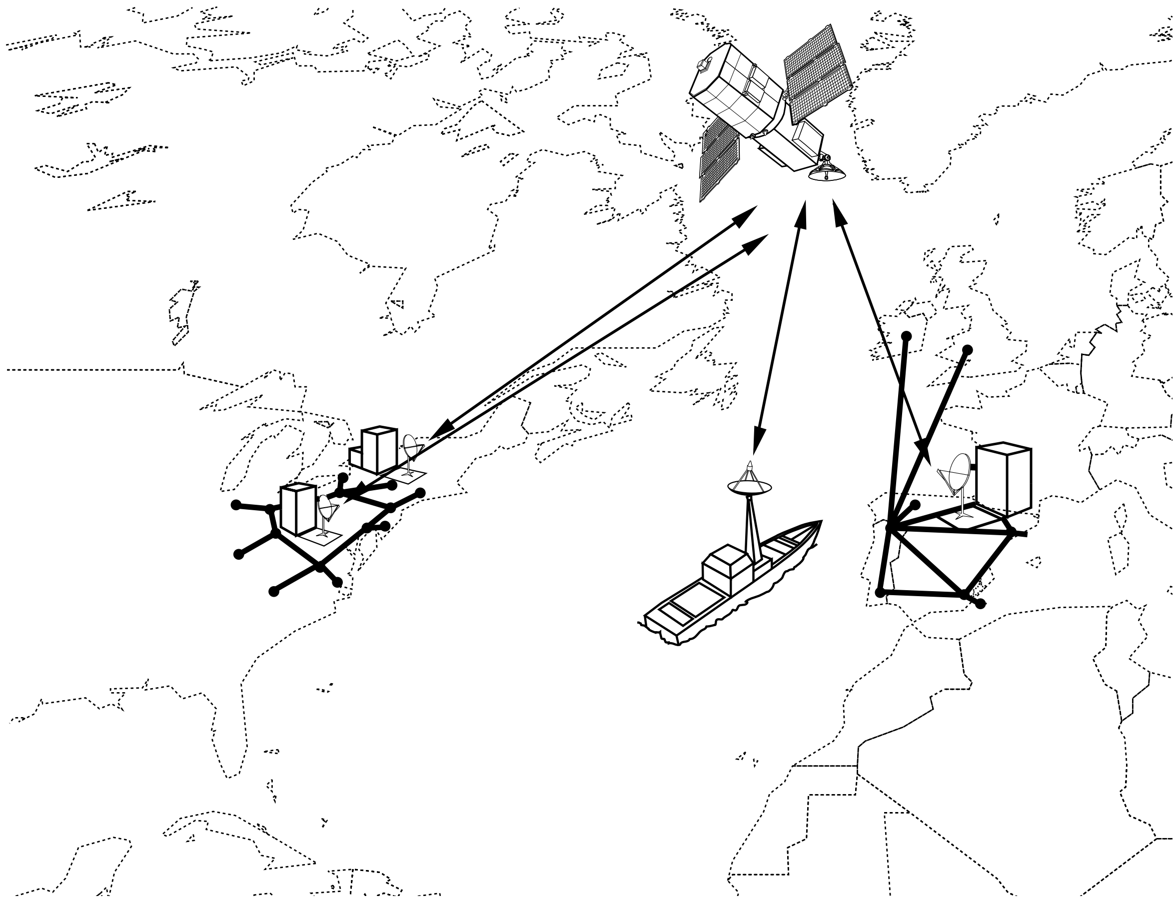

Figure 1: Satellite/Terrestrial Connections

1a) *Satellite Applications*

The wideband service suggested herein refers to applications requiring bandwidth on the order of tens to hundreds of MHz or transfer rates of the same magnitude (e.g., SONET, ATM, B-ISDN). Such wideband services are normally intended for delivery over optical fiber. When the fiber is available, this is probably the most practical form of delivery. However, there are situations in which a space-based network can be advantageous.

There are several inherent access capabilities of satellite systems which make them highly attractive for certain applications. Space-based systems can easily provide access to:

i) remote sites, anywhere within their field of view
ii) mobile sites, such as ships at sea, motor vehicles, or aircraft.

Additionally, a satellite link can:

iii) be established on a temporary basis, for special events
iv) be used to bypass a congested or damaged terrestrial network
v) provide "bandwidth on demand".

The constraints on such capabilities include the capabilities of the satellite(s) used, and the capabilities and logistics of the ground stations. utilizing the satellite(s).

1b) *ACTS and the GSN*

The NASA Advanced Communications Technology Satellite (ACTS) has the bandwidth and routing capability to provide wideband, networked interconnections [1]. The High Data-Rate (HDR) Ground Stations used in the ACTS Gigabit Satellite Network (GSN) were designed to provide fiber-like service. The ground stations and the system software were constructed by BBN Systems and Technologies (Cambridge, MA) and Motorola Government Systems and Technology Group (Scottsdale, AZ) under a program jointly funded by NASA and ARPA. For a detailed description of the GSN, please see [2,3,4].

2) Bandwidth and Signal Quality

Two of the most advantageous characteristics of optical fiber are its virtually unlimited bandwidth and its inherently low bit-error rate (on the order of 10^{-11}). Conventional satellites, on the other hand, typically have bandwidth on the order of tens of MHz, with link bit-error rates in the range of 10^{-5} - 10^{-6}. This type of performance is adequate for applications such as low-rate data and television distribution, but in order to provide fiber-like service, both the bandwidth and signal quality of the satellite links must be improved.

The ACTS satellite "transponder" has a bandwidth of at least 800 MHz* [5]. This is sufficient to pass a 622 Mb/s data stream, with overhead, using Offset-QPSK modulation (the null-to-null bandwidth of the main lobe of the modulated signal is 696 MHz). Unfortunately, the best raw channel bit-error rate that can be achieved at these rates with the ACTS is about 10^{-6}--inadequate for compatibility with fiber-based service. However, in the Gigabit Satellite Network, ultimate bit-error rates of 10^{-11} - 10^{-12} are achieved by using Reed-Solomon block coding.

The Reed-Solomon encoding has two inherent characteristics which are ideally suited to this specific application: byte interleaving and a very high coding gain. (although the two are interrelated). Satellite links often suffer from bursts of errors--as opposed to uniformly distributed error arrivals. The byte interleaving protects against such bursts of errors by re-distributing received errored bits across many codewords, which have a small number of correctable errors in each. The high coding gain overcomes the somewhat weak satellite bit-error rate performance by providing post-FEC bit-error rates of better than 10^{-11} with input BERs of 10^{-5} or greater.

In the HDR ground stations, the Reed-Solomon coding is performed by an integrated circuit manufactured by LSI Logic (Milpitas, CA). As a further enhancement of signal quality, the HDR ground stations utilize a dual-rate burst satellite modem, which can provide channel throughput at 622 Mb/s (in QPSK mode) or 311 Mb/s (in BPSK mode)--the BPSK mode providing more than 3 dB of extra margin (the actual burst rate of the modems is either 696 or 348 Mb/s). The selection of mode is made on a burst-by-burst basis, i.e., a channel can be configure to use either modulation scheme.

Typical received carrier-to-noise density ratios are from 101 to 104 dB Hz. Corresponding performance numbers are indicated in Table 1.

**--Due to the hard-limiting characteristic of the ACTS transponder channel, the absolute bandwidth is not well defined. It is however, possible to pass the above mentioned signal through the channel without irrevocable degradation*

Table 1: ACTS GSN Typical BER Performance

received C/N_o (dB Hz)	mode	E_b/N_o (dB)	link throughput rate (Mb/s)	raw channel BER	post-FEC BER
104	QPSK	15.6	622	2×10^{-6}	$< 10^{-11}$
101	QPSK	12.6	622	8×10^{-5}	$< 10^{-11}$
104	BPSK	18.6	311	$< 10^{-11}$	$< 10^{-12}$
101	BPSK	15.6	311	4×10^{-11}	$< 10^{-12}$

The minimum C/N_O required for post-FEC BER of less than 10^{-11} is about 100 dB Hz for a QPSK channel, and about 94 dB Hz for a BPSK channel. This yields rain fade margins between 1 and 4 dB for QPSK, and between 7 and 10 dB for BPSK. To date, the system has exhibited no link failures due to rain.

The combination of the wide satellite transponder bandwidth and the error performance of the HDR ground stations provides links of sufficient bandwidth and quality similar to that of optical fiber.

3) Terrestrial Compatibility

3a) *Networking*

Traditional satellite service consists of point-to-point links, which are run either continuously or in a TDMA-mode. The ACTS satellite can mimic a multi-node network through it's switchable electronically-hopped antennas and its microwave switch matrix. These two features provide true SS-TDMA (satellite-switched time-division multiplex) capability.

The satellite can provide three simultaneous uplinks and three downlinks, their locations on the earth and their interconnection switchable on either 1 or 32-_ sec boundaries. By programming the microwave switch matrix and the antenna spot selections, mesh connections can be made between several ground stations in the network, each acting either as isolated terminal or as a node in a terrestrial network.

In the GSN, the ground stations' terrestrial interface ports are connected to local fiber networks, and the ground stations and satellite are configured to provide SONET OC-3 or OC-12 connections between these ports. The local networks are then interconnected through the satellite network.

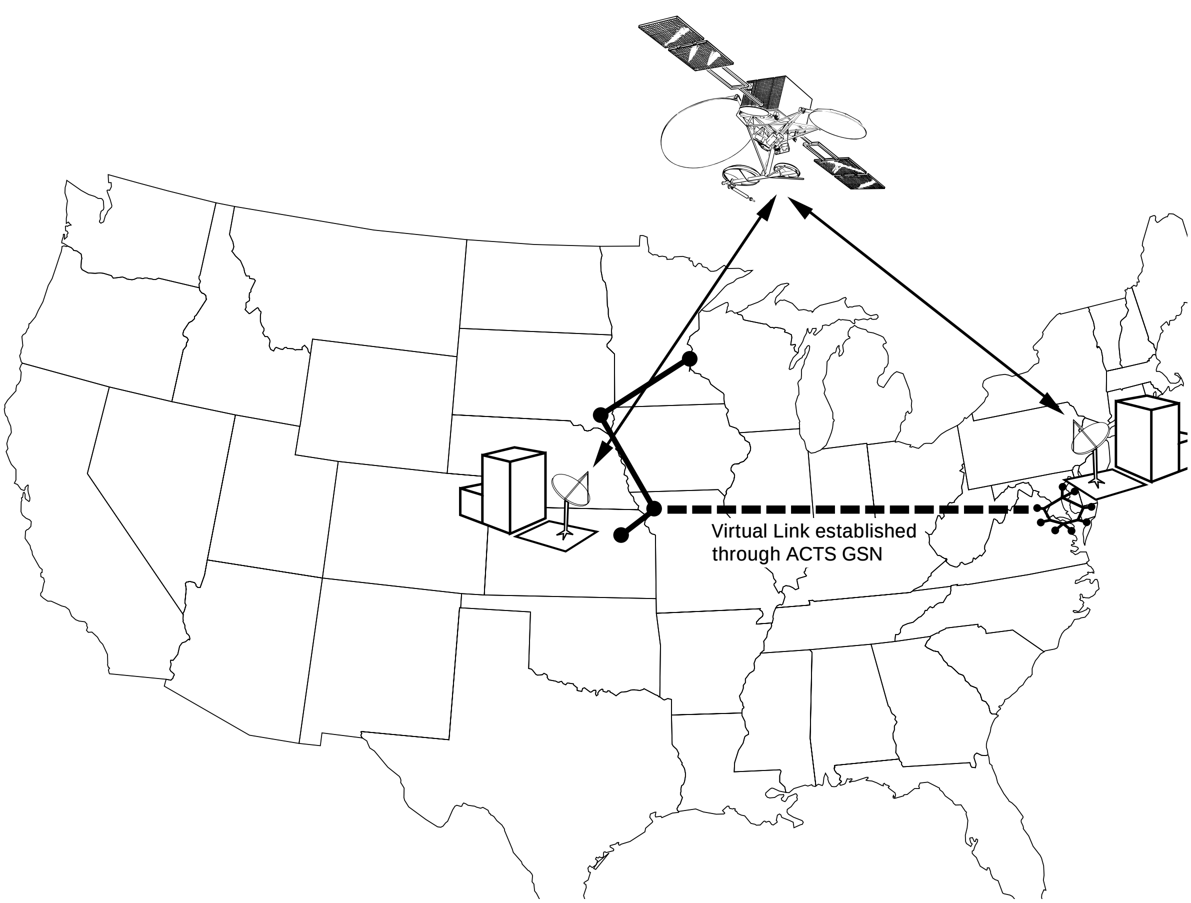

Figure 2: Network Interconnection via the ACTS GSN

3b) SONET

To be compatible with terrestrial networks, it is necessary for a space-based network to conform to the OSI system of protocol layers. The GSN provides connectivity at Layer 0--physical layer.

The input and output ports to the ground stations are SONET OC-3 or OC-12 optical interfaces. The GSN serves as SONET Line Terminating Equipment (LTE) and will support most of the SONET overhead functions. The details are provided in Table 2 [3].

Table 2: Support of Section and Line Overhead Functions in the SONET Interfaces of the Gigabit Satellite Network

Section Overhead	
Framing and STS-1 ID	yes
Section Error Monitoring (BIP-8)	yes
Section DCC, Section Orderwire, and User Channel	no
Line Overhead	
Pointer Bytes and Pointer Action Byte	
- Frequency justification	yes
- Alarm Indication Signal (AIS)	yes
Automatic Protection Switching (APS)	
- Line switchover	no
- Far End Receive Failure (FERF)	yes
Line DCC and Line Orderwire	no

In the uplink direction, the incoming STS-1 components of a non-concatenated STS-3 or STS-12 signal first have their payloads separated from their section and line overheads, and are then individually aligned to an internal 32-msec frame signal, which is phase locked to the satellite MSM frame. The STS-1 signals stripped from their section and line overheads (payload plus-payload-pointers only) are then routed independently over satellite to different earth stations. In the downlink direction, the outgoing OC-3 or OC-12 signal is built first by assembling the aggregate signal from received STS-1 payload plus-payload-pointer bytes originating in different earth stations, and then by multiplexing these payload signals with locally generated SONET section and line overhead bytes.

3c) *ATM*

The transmission of ATM cells poses no inherent difficulties to the GSN, or any satellite network that provides similar physical-layer compatibility. As no routing or processing of the cells is performed by the satellite network itself, the ATM cells are simply transmitted and received through the SONET Line Terminating Equipment--the satellite network serves as a "wire" between ATM switches.

The overriding problem with ATM over satellite arises from the criterion used for discarding errored cells. In normal ATM header processing, the cell is discarded ("dropped") if more than one of the header bits is errored, and cannot be corrected by the header CRC. If a "dropped" ATM cell constitutes the entire 424-bit cell being errored, it can be argued [9] that the BER of an ATM link is approximately 17,000-times the channel BER. With the typical bit error-rates provided by optical fiber (usually better than 10^{-11}), this is not a problem. However, with the typical satellite link BER of 10^{-6} - 10^{-7}, the ATM link is simply unusable. The FEC used in the GSN alleviates this problem, and ATM has been used extensively with this system [7].

4) Latency and Higher Level Computer Communication Protocols

4a) *Transport Layer*

The major obstacles encountered with wideband computer communication over a geostationary satellite link are due to the latency introduced by the distances to and from the satellite. The path length to geostationary orbit is approximately 35600 km. This gives a delay of approximately 120 msec from the ground to the satellite, or 240 msec for each round trip. In the case of protocols requiring acknowledgments for packets (such as TCP), the wait is now 480 msec (almost one-half second). With an OC-3 connection, this means that there are about 10 MB "in the pipe" before an acknowledgment can be received, i.e. the delay-bandwidth product for this situations is about 10 MB. In order get any real throughput from this sort of delay-bandwidth constraint with TCP requires the TCP window size to be increased to as large as possible.

Srinidhi has demonstrated [7] throughput to 58 Mb/s (for TCP), and UDP throughput approximately 120 Mb/s (after including allowances for various protocol overheads) using a TCP window size of 4 MB and OC-3 (155 Mb/s) connections through the ACTS GSN. It is important to note that the TCP throughput is a direct function of the window size available with the software and hardware used for the application.

4b) *Modifications*

In order to get reasonable throughputs with this order of delay-bandwidth product, certain modifications need to be made to the transport layer protocols. Some possibilities include:

- i) increase window sizes
- ii) replace Stop_and_Wait with a Go_Back_N protocol for acknowledgments
- iii) defeat TCP slow start and related parameters that effect performance on long round-trip transit delay links.
- iv) use direct routing where possible.

5) Application Experience

5a) *The Lewis-Boeing Experiment*

This was the first application experiment performed with the GSN. This ACTS experiment explored the implementation of a “numeric wind tunnel”, through the remote use of a NASA Cray supercomputer. A workstation at Boeing was linked into an ACTS high data rate earth station at their Seattle, WA facility. The other earth station was connected to the Cray via the campus ATM fiber network at NASA Lewis Research Center in Cleveland, OH. [7].

The path at the Lewis (Cray) end consisted of the ground station SONET ports connected through a Fore ATM switch into the Lewis ATM network. The Cray connected to the same ATM network in two ways; either by a proprietary Cray device (Cray Bus-Based Gateway), or a Gigarouter.

At the Boeing end, the ground station was connected to a matching ATM switch. A workstation with an ATM interface was also connected to the same switch. The workstation provided the user interface to the Cray. An experimental ATM traffic processor was also inserted into this network to collect traffic statistics.

The application used to permit distributed processing between the Cray and the workstation is known as PVM (Parallel Virtual Machine). The rest of the protocol stack consisted of modified TCP, IP, ATM, and finally SONET.

As stated earlier, by modification of the TCP window size to 4 MB, and various other adjustments, throughputs of 58 Mb/s (for TCP), and 120 Mb/s (UDP) were possible. The 4 MB window size was a limitation of the workstation. With a larger window size, the throughput can be increased.

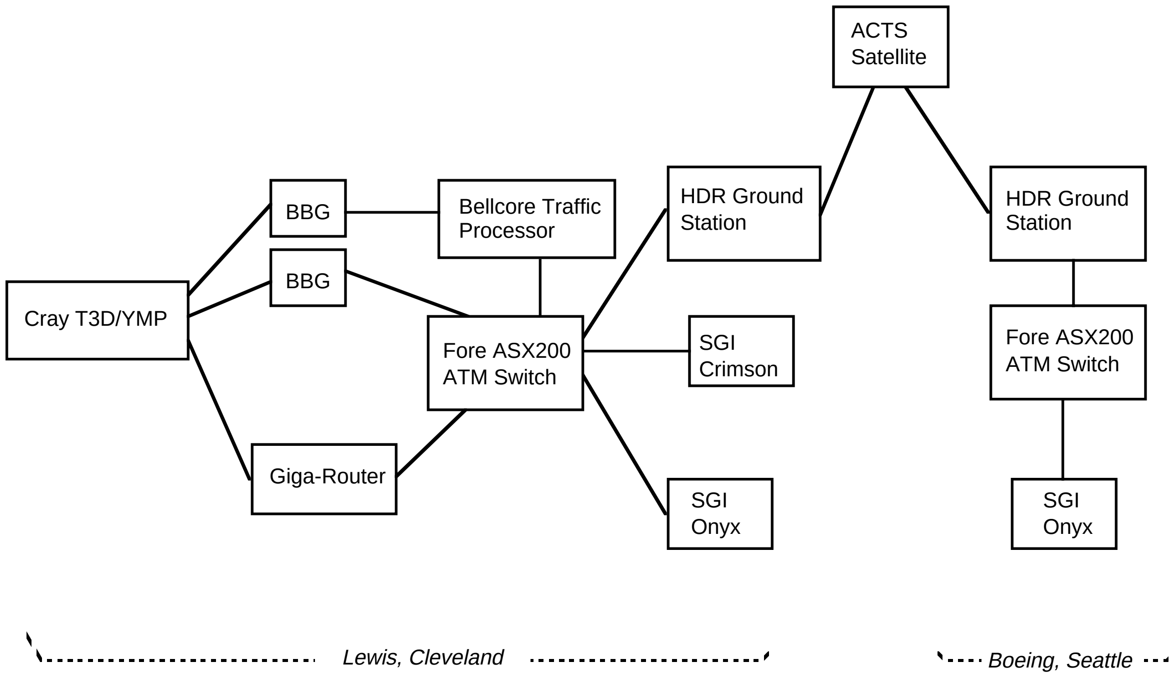

Figure 3: Lewis/Boeing Experiment Hardware Configuration

5b) *The NCAR-OSC Experiment*

The experiment consisted of the interconnection of two Cray supercomputers, one at the National Center for Atmospheric Research (NCAR) in Boulder, CO and the other at the Ohio Supercomputing Center (OSC) in Columbus, OH. The two supercomputers interactively exchanged large numerical models of atmospheric and lake conditions for the modeling of climate simulations in the Great Lakes area. This enabled meteorological and marine forecasting through the use of complex supercomputer models and access to unique and geographically diverse resources. In addition to enhanced conventional audio and visual techniques, this multiple site collaboration used a video whiteboard which allowed for interactive drawing, writing, and posting of images and text [8].

The Crays were connected without an intermediate ATM network. Each Cray's HiPPI bus interface was connected to a proprietary HiPPI-to-SONET converter, developed by The Los Alamos National Laboratory. The SONET ports of the converter were then connected to the ground stations via a HiPPI switch. The switch is connected directly to the ground station ports. The hardware at each site was identical.

This experiment also used PVM for the distributed processing. The rest of the protocol stack was TCP, IP, HiPPI, down to SONET.

The Cray machines permitted a larger window size (10 MB) than the workstation in the Lewis/Boeing experiment. With the 10 MB window, NCAR has achieved throughputs over 120 Mb/s with TCP, in a 155 Mb/s OC-3 channel.

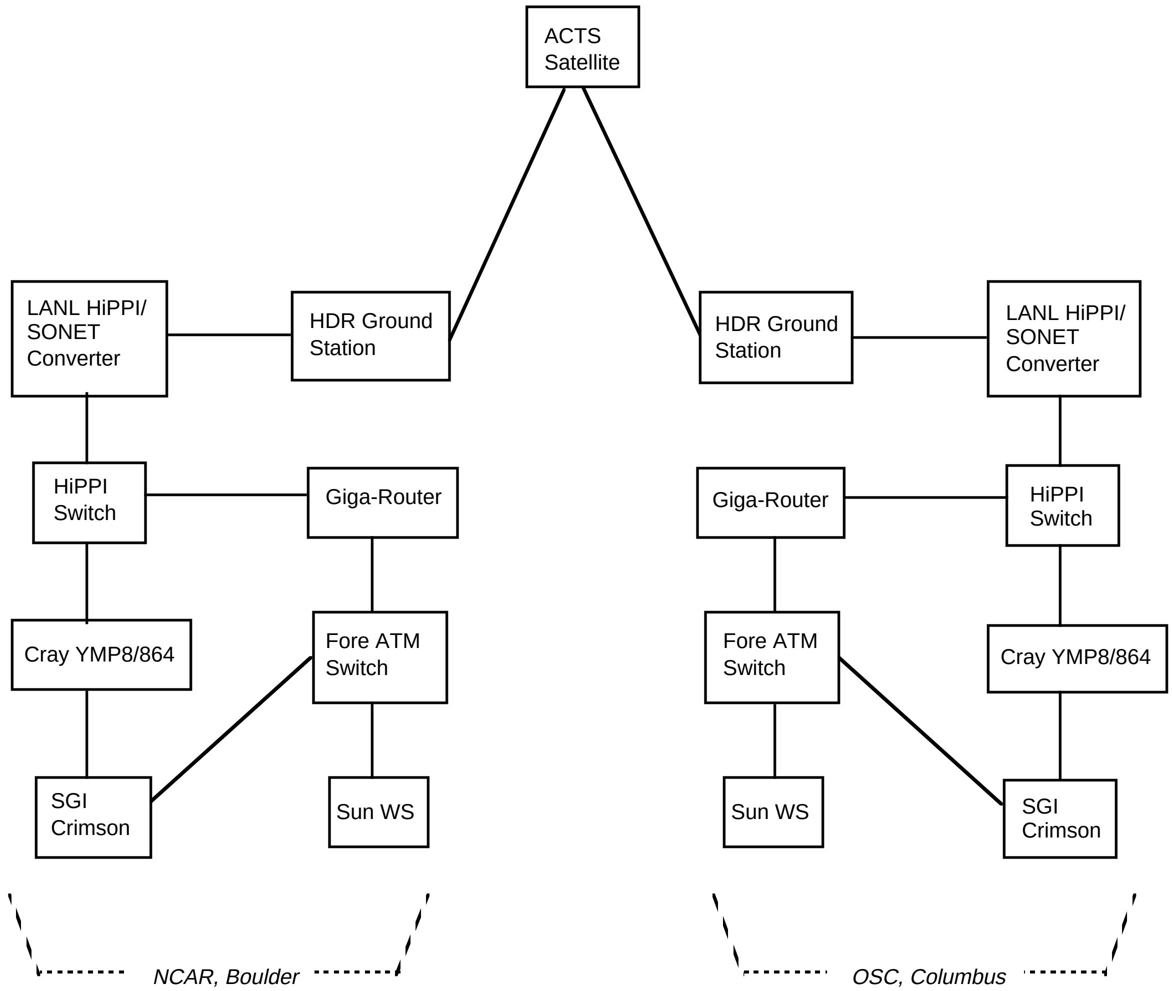

Figure 4: NCAR/OSC Experiment Hardware Configuration

6) Conclusions

NASA's goal is to demonstrate advanced space-based communications technologies, such as those which comprise ACTS, and how these technologies will play a key role in the development of a true Global Information Infrastructure. To this end, the ACTS Gigabit Satellite Network has demonstrated compatibility with high-speed terrestrial optical fiber service. This proof-of-concept allows conventional SONET service, as well as emerging services, such as ATM to be transmitted over broadband satellite systems. However, due to latencies associated with geostationary satellites, the communications protocols need to be modified (and potentially re-defined) to make more efficient use of these advanced schemes. Some ACTS experiments have investigated these protocol issues and have attempted to quantify the issue and examine alternative methods.

In the future, wideband satellites should play a significant role in complementing terrestrial fiber networks. This is especially true for applications in need of access to remote or mobile locations, underserviced regions, or added network agility. Besides the development and test of the Gigabit Satellite Network, and the two actual experiment field trials cited in this paper, the ACTS High Data Rate Experiments Program will continue to be executed throughout the life of the satellite. These program plans include an earth station in Hawaii and complete interconnection of two Gigabit testbed terrestrial networks.

References

[1] Schertler, R. J., Crisafulli, J., "NASA Advanced Communication Technology Satellite (ACTS) An On-orbit Testbed", Pacific Telecommunications Conference, January 22-26, 1995

[2] Bergamo, M. A., "Terminal System and Capability for ARPA-NASA High-Speed SONET/ATM Experiments Over NASA's Advanced Communications Technology Satellite", MILCOM '93, pg. 235-241.

[3] Bergamo, M. A., "Network Architecture and SONET Services in the NASA/ARPA Gigabit Satellite Network using NASA's Advanced Communications Technology Satellite (ACTS)", 15th AIAA International Communications Satellite Systems Conference, pp. 208-216, February 28-March 3, 1994.

[4] Bergamo, M. A, Hoder, D. J.,"Gigabit Satellite Network Using NASA's Advanced Communications Technology Satellite (ACTS): Features, Capabilities, and Operations", Pacific Telecommunications Conference, January 22-26, 1995

[5] Hoder, D., Kearney, B., "High Data-Rate Ground Station for the ACTS Gigabit Satellite Network (GSN)", NASA ACTS Results Conference, September 11-13, 1995

[6] Kearney, B. and Lee, K. "High Data Rate Modem for Support of ACTS Gigabit Network", 15th AIAA International Communications Satellite Systems Conference, February 28-March 3, 1994.

[7] Brooks, D. E., Carrozzi, T. M., Dowd, F. W., Lopez, I., Pellegrino, S. M., Srinidhi, S. M., "ATM Based Geographically Distributed Computing Over ACTS", ACTS Results Conference, September 11-13. 1995

[8] Carlson, W.E., Spencer, S. N., Geroch, M., Lewis, M., Bedford, K., Welsh, D., Kelley, J., Welch, A., "Visualization Of Results From A Distributed, Coupled, Supercomputer-Based Mesoscale Atmospheric And Lake Models Using The Nasa Acts", ACTS Results Conference, September 11-13. 1995

[9] personal communication with Jon C. Freeman

[10] Bellcore TR-NWT-000253, "Synchronous Optical Network (SONET) Transport Systems: Common Generic Criteria", Issue 2, December 1991.

[11] ANSI T1.105-1991, "Digital Hierarchy - Optical Interface Rates and Format Specifications (SONET)", July 2, 1991.